Main-Sequence Fitting Distance to the σ Ori Cluster

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Received ______________________; accepted ______________________

ABSTRACT

The σ Ori cluster is an unbound aggregate of a few hundred young, low–mass stars centered on the multiple system σ Ori. This cluster is of great interest because it is at an age when roughly half of the stars have lost their protoplanetary disks, and the cluster has a very large population of brown dwarfs. One of the largest sources of uncertainty in the properties of the cluster is that the distance is not well known. The directly measured Hipparcos distance to σ Ori AB is 350^{+120}_{-90} pc. On the other hand, the distance to the Orion OB1b subgroup (of which σ Ori is thought to be a member), 473±40 pc, is far better determined, but it is an indirect estimate of the cluster's distance. Also, Orion OB1b may have a depth of 40 pc along our line of sight. We use main sequence fitting to 9 main sequence cluster members to estimate a best fit distance of 420±30 pc, assuming a metallicity of −0.16±0.11 or 444 pc assuming solar metallicity. A distance as close as 350 pc is inconsistent with the observed brightnesses of the cluster members. At the best fit distance, the age of the cluster is 2–3 Myrs.

Subject headings: open clusters: general — young stars: individual(σ Ori)

1. Introduction

The bright O9.5V star σ Ori is a trapezium–like system with six known components. The brightest component, σ Ori AB (V=$3.^{m}80$), is a $0.25''$ binary (Horch et al. 2001) with an O9V primary and a B0.5V secondary (Edwards 1976) and an orbital period of $\sim$170 years or $\sim$158 years (Heintz 1974, 1997). The O9V primary, σ Ori A, is itself a double lined spectroscopic binary[1] (Peterson 2006; Bolton 1974; Miczaika 1950). The spectral type of σ Ori C is A2V. The D and E components are B2V stars with V$\simeq$6.8 and $\simeq$6.6 respectively (see Table 1).

The σ Ori cluster was first recognized as a group of high–mass stars by Garrison (1967), and as cluster of low–mass pre-main-sequence stars by Walter, Wolk, & Sherry (1998). Continuing work on the cluster has revealed a young cluster of several hundred low–mass stars (Sherry et al. 2004; Burningham et al. 2005; Kenyon et al. 2005) and a rich population of brown dwarfs (Béjar et al. 1999, 2001; Béjar, Zapatero Osorio, & Rebolo 2004; Zapatero Osorio et al. 2002). About one third to one half of the stars retain their accretion disks (Oliveira, Jeffries & van Loon 2004; Hernández, et al. 2007). The cluster is considered part of the Orion OB1b association. Age estimates for Orion OB1b range from less than 2 Myrs (Brown, de Geus, & de Zeeuw 1994) up to 7 Myrs (Blaauw 1991). This is an exceptionally interesting age because it is the age when protoplanetary disks are making the transition from optically thick to optically thin and may be the age when giant planets form. The more accurately the cluster age can be measured, the tighter the constraint on disk lifetimes and the time available for giant planet formation will be. See Walter, et al. (2008) for a recent review of observational data on the low–mass population of the σ Ori cluster.

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[1]We wish to thank Deane Peterson for sharing unpublished results of his observations of σ Ori AB with us.

The most significant source of uncertainty for the age of this cluster is the uncertain distance to the cluster. Many authors adopt the Hipparcos distance of 350^{+120}_{-90} pc for σ Ori (Perryman et al. 1997) as the distance to the center of the cluster. This has the virtue of being a direct measurement of the distance to the cluster, but it has an uncertainty of 30% (see Schroeder et al. (2004) for a discussion of biases on Hipparcos parallaxes of O stars). Others use the Hipparcos distance to the Orion OB1b subgroup (of which σ Ori is a member), 473$\pm$40 pc (deZeeuw et al. 1999), as the distance to the cluster. This value is more precise because it is the average distance to 42 members of the association, yet it is only an indirect measurement of the distance to σ Ori. Similarly, Hernández, et al. (2005) find a distance of 443$\pm$16 pc from the Hipparcos parallaxes of the combined Orion OB1b and 1c subgroups. The Orion OBIb association has a size of $\sim$30–40 pc across the sky, so it is likely to have a similar depth along our line of sight. The cluster could easily lie $>$20 pc in front of or behind the center of Orion OBIb. It would be preferable to have a direct measure of the cluster's distance that is more precise than the Hipparcos distance to σ Ori.

In a brief abstract, Garrison (1967) said that main sequence fitting to 15 B stars near σ Ori yielded a narrow main sequence at a distance modulus of 8.2 (440 pc). Garrison did not correct for the small values of reddening that some of the likely cluster members have. Garrison does not appear to have ever published a more detailed description of this result.

In this paper we re–examine the main sequence fitting distance for the σ Ori cluster using published spectroscopy and photometry for the stars that lie within $30'$ of σ Ori AB and have spectral types earlier than F0.

2. Analysis and Data

We searched the literature[2] for photometry and spectral types for all of the stars within 30′ of σ Ori AB that have spectral types earlier than F0. Several of the stars have B and V photoelectric photometry from multiple observations taken prior to 1980. Table 1 collects our adopted colors and magnitudes for the 19 stars we selected.

We have also obtained new spectra of those stars whose spectral types or colors appeared discrepant. These spectra, obtained with the SMARTS/CTIO 1.5m RC spectrograph, have 1.6Å resolution between about 3880 and 4500Å. Spectral types have been determined through visual comparison with a grid of spectral standards obtained with the same same instrument.

2.1. Magnitudes and B−V Colors for Individual Stars

Several of the stars listed in Table 1 can not be directly compared to the main sequence because they are binaries or have known problems with their photometric data. Their photometry must be corrected before being included in any estimate of the cluster distance.

2.1.1. σ Ori Aa, σ Ori Ab, and σ Ori B

σ Ori A and σ Ori B are the two brightest cluster members. This visual pair, with a separation of 0.25″, lies roughly at the center of the cluster. Horch et al. (2001) used speckle observations to derive a V band magnitude difference of $1.^m25$. Similar results were found by Ten Brummelaar et al. (2000) who report ΔV=$1.^m24$. Given a combined magnitude of V=$3.^m8$ and an E(B−V) of $\sim0.^m06$ (see section 2.2), a magnitude difference

[2]Our initial search relied heavily upon the SIMBAD data base.

of $1.^m25$ indicates that σ Ori A has $V_0 \simeq 3.^m91$ while σ Ori B has $V_0 \simeq 5.^m16$.

σ Ori A is itself a double-lined spectroscopic binary. Bolton (1974) estimated a ΔV of $\sim 0.^m5$ between σ Ori Aa and σ Ori Ab. This would require σ Ori Aa and Ab to have $V_0 \sim 4.^m4$ and $\sim 4.^m9$, respectively. There is no measured spectral type for σ Ori Ab yet, so its UBV colors are unknown. Assuming that it is on the ZAMS, the spectral type a star that is $0.^m5$ fainter than an O9V star should B0V.

Edwards (1976) quotes spectral types of O9V and B0.5V for σ Ori A and B, respectively. Assuming an uncertainty of ± 0.5 subtypes, we adopt values of $(B-V)_0 \simeq -0.^m31 \pm 0.01$ for σ Ori Aa and $(B-V)_0 \simeq -0.^m28 \pm 0.02$ for σ Ori B (Kenyon & Hartmann 1995).

The observed B$-$V for σ Ori AB is $-0.^m24$. Assuming an intrinsic color $(B-V)_0 = -0.^m30$ for σ Ori AB , E(B$-$V) must be $\sim 0.^m06$. This is consistent with the observed N(H) column density of 3.3×10^{20} cm^{-2} (Fruscione et al. 1994; Bohlin et al. 1983). The uncertainty on the column density is 20%. This value is also consistent with published estimates of the line of sight reddening to σ Ori AB (e. g. Lee (1968)) and with the N(H) column density of 3.6×10^{20} cm^{-2} measured by Shull & Van Steenberg (1985).

2.1.2. σ Ori C

Greenstein & Wallerstein (1958) measured the B and V magnitudes of σ Ori C. They noted that the observed B$-$V color of σ Ori C, $-0.^m02$, is too blue for its spectral type, A2V, which should have $(B-V)_0 = 0.^m06$ (Kenyon & Hartmann 1995). Greenstein & Wallerstein (1958) account for the exceptionally blue color of σ Ori C as the result of scattered light from σ Ori AB ($11''$ away) in the aperture of the photometer. The published V magnitude is $8.^m79$ (Greenstein & Wallerstein 1958), but that measurement was also contaminated by scattered V band light from σ Ori AB. Greenstein & Wallerstein (1958) estimate that,

after correcting for scattered light, the true V magnitude of σ Ori C is $\sim 9.^{m}2$.

Sherry et al. (2008) report recent differential V and I_C photometry for stars within $6'$ of σ Ori AB. While σ Ori AB is saturated, C, D, and E are not saturated. They find that σ Ori C is $2.^{m}63\pm0.01$ magnitudes fainter than σ Ori D, and $2.^{m}74\pm0.01$ magnitudes fainter than σ Ori E in the V band. Using the V magnitudes from Table 1 for σ Ori D and σ Ori E yields $V=9.^{m}44$ and $V=9.^{m}40$ respectively for σ Ori C. These measurements were done using small apertures which are not significantly contaminated by scattered light. We will adopt $V=9.^{m}42\pm0.02$ for the magnitude of σ Ori C (uncorrected for reddening).

2.1.3. σ Ori D

The three papers that report UBV photometry for σ Ori D quote significantly different V magnitudes, and to a lesser extent, colors. Greenstein & Wallerstein (1958) report a V magnitude of $6.^{m}62$. Eighteen years later, Vogt (1976) reported a V magnitude of $6.^{m}73$. Guetter (1979) reported a V magnitude of $6.^{m}84$. These discrepant V magnitudes may indicate variability, or that stray light from σ Ori AB affected the measurements of σ Ori D. Mermilliod & Mermilliod (1994) list a weighted averaged of the UBV photometry for σ Ori D which we have used in Table 1.

2.1.4. σ Ori E

The B2Vp star σ Ori E has unusually strong He lines (Greenstein & Wallerstein 1958) which make it spectroscopically peculiar. It has variable line widths and photometric variations (Δmag$\sim 0.^{m}03$–$0.^{m}15$) with a period of 1.19 days (Hesser, Walborn, & Ugarte 1976; Townsend, Owocki, & Groote 2005). There are conflicting opinions as to whether σ Ori E is physically associated with σ Ori AB. Much of the uncertainty surrounding

the membership of σ Ori E with σ Ori AB follows from uncertainty on the mass and evolutionary status of σ Ori E. Greenstein & Wallerstein (1958) estimated the absolute magnitude of σ Ori E using three different methods, thereby placing the star on or near the main sequence (which would put σ Ori D, and σ Ori E at the same distance). They found that the equivalent widths of two components of the interstellar K line are similar for both σ Ori AB and σ Ori E, as are the radial velocities. Attempts to model the UV flux from the V band flux and spectroscopic features lead to models of σ Ori E that have masses that are far too small ($\sim$3 $M_\odot$) for an early B main sequence star (M$\sim$9 $M_\odot$). The main reason for the low masses in these models is that the profiles of the Balmer and helium lines indicate a low gravity (Hunger, Heber, & Groote 1989). More recent models postulate emission from plasma clouds magnetically confined above the photosphere (Townsend, Owocki, & Groote 2005) which may explain the discrepancy between the gravity estimated from line profiles and data that indicate that σ Ori E is a main sequence star. Given the significant uncertainties on the models, we take the observations indicating that σ Ori E is a main sequence star with a normal mass and radius for its spectral type at face value.

A B2V star has $(B-V)_0$ of $-0.^m24$ (Kenyon & Hartmann 1995). The measured B$-$V for σ Ori E is $-0.^m18$ (Guetter 1979), which makes E(B$-$V) $0.^m06$. This is consistent with the observed N(H) column density of 4.5×10^{20} cm^{-2} (Fruscione et al. 1994; Shull & Van Steenberg 1985). The uncertainty on the column density is 20%.

2.1.5. BD −02 1323C and HD 294272

BD −02 1323C was not found by our initial SIMBAD search for early type stars within 30′ of σ Ori. This star came to our attention because SIMBAD notes that HD 294272 is a member of a triple system, ADS 4240 (Aitken 1932). ADS 4240A is HD 294271.

ADS 4240B is HD 294272 which is separated from HD 294271 by ∼68″. ADS 4240C (BD −02 1323C) is separated from HD 294272 by 8.5″. SIMBAD listed a V magnitude of $10.^m3$ for BD −02 1323C, and no other photometric measurements. This value is not correct.

Guetter (1979) reported photometry for BD −02 1323A and BD −02 1323B. Guetter (1981) used the same names when he reported the spectral types. SIMBAD, which does not recognize the names BD −02 1323A and BD −02 1323B, assigned the Guetter (1979) photometry for BD −02 1323B (ADS 4240C) to BD −02 1323 which is ADS 4240B or HD 294272. Consequently, HD 294272 (ADS 4240B) was listed in SIMBAD as having the photometry and spectral type of BD −02 1323C (ADS 4240C). The measurements for the two stars from Guetter (1979, 1981) and Mermilliod & Mermilliod (1994) have been correctly assigned in Table 1.

2.1.6. HD 294273 & HD 294279

We obtained new spectra for HD 294273 & HD 294279 since the only published spectral types that we could find are A2 and A3, respectively, in the HD catalog. The Ca II K lines are far too strong for early A spectral types. The revised spectral types are early F (F0-F3) for HD 294279 and A7 for HD 294273. We do not assign a luminosity class, but it is likely that they are both class V.

2.2. Reddening

We estimate the reddening of most of the stars in our sample by comparing the observed B−V color to the $(B-V)_0$ expected for each star's spectral type, and computing A_V assuming R=3.1. Column 8 of Table 1 lists these A_V values for probable cluster

members. The mean E(B−V) for probable cluster members is $0.^m06\pm0.005$ (σ Ori A and B were treated as a single measurement). The median E(B−V) is also $0.^m06$. All of the probable cluster members have values of E(B−V) between $0.^m04$ and $0.^m09$, which is consistent with the $0.^m015$ uncertainty on E(B−V) for individual stars. The mean E(B−V) of $0.^m06\pm0.005$ makes the mean A_V of the cluster $0.^m19\pm0.02$, in agreement with the values quoted by Lee (1968); Shull & Van Steenberg (1985) for σ Ori AB.

Assuming that E(U−B)=0.72E(B−V), we expect a mean E(U−B)$\sim0.^m04$ mag. This is comparable to or smaller than the uncertainties on $(U-B)_0$ due to the change in $(U-B)_0$ from one spectral type to the next along the ZAMS. We found a median E(U−B) of $0.^m02\pm0.03$ with most of the stars in Table 1 having values ranging from $-0.^m06$ to $0.^m07$. HD 37633 (V1147 Ori), a known variable, does have an exceptionally large, negative E(U−B)=$-0.^m16$. This may be due to its variability or a U band excess. Our spectrum shows a spectral type of B9.5. HD 37699 also has a very blue U−B color excess with E(U−B)=$-0.^m11$. Since these two have values of E(U−B) that are significantly less than zero, we excluded these stars from the calculation of the median E(U−B). Our median E(U−B) is consistent with our mean E(B−V) and a normal reddening law.

The small reddening has a disproportionate impact on main-sequence fitting on the V, B-V plane because the ZAMS has a slope $\frac{\Delta V}{\Delta(B-V)}$ $\sim$18 for stars near B5V. If we were to ignore the cluster's reddening, we would find a distance that is $\sim$100 pc smaller than we find when correcting for the observed color excess.

2.3. The Main Sequence Turn–On

Since the σ Ori cluster is roughly 3 Myrs old, most of the cluster members have not reached the ZAMS. Figure 1 compares the ZAMS of Turner (1976, 1979) to theoretical

isochrones from Siess, et al. (2000) and Palla & Stahler (1999). These models predict that the main sequence turn–on is near very late B or very early A spectral type, depending upon the assumed age and the choice of model. Therefore we exclude the A stars in fitting the main sequence, as they are likely to lie above the ZAMS.

2.4. The Abundances of σ Ori Cluster Members

Cunha, Smith, & Lambert (1998) report that [Fe/H] for the Orion OB association as a whole is -0.16 ± 0.11. However, most of the stars in their sample were from Orion OB1c and 1d. They also report variations of the oxygen to iron ratio with position within Orion OB1, possibly due to self–enrichment by supernovae.

Metallicity changes the position of stars on the CMD in three ways. Lower metallicity stars are slightly more luminous (at a fixed mass). Lower metallicity stars also have smaller radii, and thus higher temperatures and earlier spectral types at a given mass. Among low–mass stars, lower metallicity stars also have less line–blanketing. This makes them bluer than higher metallicity stars of the same spectral type.

The $(U-B)_0$ and $(B-V)_0$ colors of early type stars are much less sensitive to metallicity than those of late type stars. From Table 1 of Cameron (1985) it is clear that B stars with only slightly sub–solar [Fe/H] should have UBV colors that are the same as those of solar metallicity stars to within $0.^m01$. This reduces our sensitivity to [Fe/H]. However, the B stars will still have lower masses than solar metallicity stars of the same spectral type. This will make the ZAMS fainter than the standard ZAMS, but not by as much as would be the case for later type stars.

We quantify the shift in the ZAMS as a function of [Fe/H] by examining the change in the M_V of isochrones from the models of Lejeune & Schaerer (2001) at $(B-V)_0$=$-0.^m21$

as the metallicity varies from z=0.040 ([Fe/H]=+0.3) to z=0.004 ([Fe/H]=−0.7). Figure 2 shows that $\Delta M_V \simeq -0.75\times$[Fe/H]. An isochrone with [Fe/H]=−0.16 is $0^m.12$ fainter than a solar metallicity isochrone and $0^m.15$ fainter than an isochrone with the metallicity of the Pleiades, [Fe/H]=+0.04. The metallicity of the Pleiades matters because we use the Pleiades to calibrate the ZAMS, so our ZAMS is matched to an [Fe/H] of +0.04 (see Section 2.6.1). Since the uncertainty on the measured value of [Fe/H] for Orion is quite large ($-0.05<$[Fe/H]< -0.3), the correction to the ZAMS is in the range $+0.^m07$ to $0.^m23$. This is a systematic correction to the distance modulus of $-0.^m15\pm0.^m08$.

2.5. Cluster Membership

Figure 3 shows a CMD with the ZAMS and isochrones over plotted. Fourteen of the stars included in Figure 3 are consistent with a distance of 420 pc and an [Fe/H] of −0.16. The A stars HD 37564 and HD 37333 are much brighter than A type cluster members should be. This suggests that they may be foreground stars or binaries.

2.5.1. HD 37564

The SIMBAD data base lists this star with a spectral type of A0V. This spectral type appears to be from the SAO catalog (SAO catalog 1966). Guetter (1981) reports a spectral type of A8V, however, the measured value of B−V is slightly bluer than $(B-V)_0$ for an A8V star (Kenyon & Hartmann 1995). If the color is correct, then HD 37564 should have a spectral type of A7 or earlier if it is reddened. In our spectrum the Balmer lines match spectral type A5 standards, while the depth of the CaII K line suggests a slightly later type of about A7.

HD 37564 is the reddest of the three bright outliers on figure 3. At spectral type A7V,

it lies roughly 1.4 magnitude above the 2.5 Myr isochrone. HD 37564 could be a foreground field star at a distance of ∼150 pc. If the spectral type is later than A7V, then the mismatch between the measured V magnitude and the expected V magnitude for a distance of 440 pc is even larger. This is consistent with previous studies that concluded that HD 37564 is probably not a member of Orion OB1 (Brown, de Geus, & de Zeeuw 1994).

2.5.2. HD 37333

HD 37333, the other obvious outlier, is 0.75 magnitudes brighter than expected for a dereddened A0V star at a distance of 440 pc. Since 0.75 magnitudes is the exact magnitude difference which an equal mass binary would have, it is quite plausible that HD 37333 is a cluster member that is an equal mass binary.

If HD 37333 is not an equal mass (or nearly equal mass) binary, then it is too bright to be a member of the cluster. If it is a main sequence field star, its likely distance modulus would be ∼310 pc. A distance of 310 pc would be consistent with membership in the Orion OB1a group, but an A0V ZAMS star would be more than 0.5 mag. fainter than an A0V main sequence field star.

2.5.3. HD 294272

HD 294272 is a member of a multiple system, ADS 4240. It is not clear if ADS 4240A (HD 294271), ADS 4240B (HD 294272), and ADS 4240C (BD −02 1323C) are a bound system or a chance alignment. The small separation between HD 294272 and BD −02 1323C (8.5″) suggests that at least these two stars are a physical system. However, HD 294272 has been classified as a B9.5III star (Guetter 1981) and is $0.^m29$ brighter than BD −02 1323C which is a B8V star. HD 294272 lies $\sim 0.^m8$ above the 2.5 Myr isochrone (Palla & Stahler

1999). The location of BD −02 1323C on the CMD is consistent with the best fit distance to the cluster. If HD 294272 and BD −02 1323C are in fact a bound pair, then HD 294272 is too bright to be a main sequence star. One possibility is that HD 294272 is a binary with a PMS companion. This would make the unresolved binary brighter and redder. Since the PMS companion would be brighter than a main sequence star of the same color, the unresolved system could be consistent with cluster membership. An alternative is that HD 294272 is not a cluster member, although this makes the small apparent separation unlikely.

2.5.4. HD 294279

As stated above, we find that HD 294279 has a spectral type of F0-F3. This is consistent with the observed B−V color of 0.39 and modest reddening. An A_V of ∼0 places the star ∼1 magnitude above the main sequence and 1 magnitude below the 2.5 Myr isochrone at the best fit distance to the cluster. This strongly suggests that HD 294279 is a foreground field star.

Caballero (2006) report a spectral type of F3 to F5 and the detection of Li in the spectrum. If the spectral type were as late as F5, then HD 294279 would lie near the isochrone, but its observed B−V is 0.39 which is much too blue for an F5 star with the clusters measured E(B−V). Such a star should have B−V=0.50. The detection of Li in the spectrum suggests that HD 294279 may be a member of Orion OB1a. HD 294279 lies closer to an 11 Myr old isochrone at 330 pc than it does to the σ Ori isochrone.

2.5.5. HD 294273

With a revised spectral type of A7, HD 294273 has an A_V which is the same as that of cluster members. It also lies on the ZAMS for a distance of 440 pc. However, for it to be a cluster member it would need to be ∼5 Myrs older than the age of the cluster. Since there is no evidence for such a large age spread, we think that it is far more likely that HD 294273 is a field star. It is probably slightly more distant than the σ Ori cluster because stars on the main sequence are brighter than stars of the same spectral type on the ZAMS.

2.6. The Cluster's Distance

Fourteen of the 19 O, B, and A stars in our sample lie close to the 2.5 Myr isochrone on Figure 3. Of these, only 10 of the O and B–stars lie on the main sequence. Three of these stars, σ Ori Aa, Ab, and B, do not have directly measured colors. We have used the observed spectral types of σ Ori Aa and σ Ori B to estimate their $(U-B)_0$ and $(B-V)_0$ colors, but there are no measurements of the spectral type or colors for σ Ori Ab. This makes σ Ori Ab unusable, leaving us with 9 usable main sequence cluster members. The stars which we have used to determine the cluster's distance are marked with an asterix in column 11 of Table 1.

We estimate the best fit distance to the σ Ori cluster by calculating χ^2_ν for the colors and magnitudes from Table 1 compared to two versions of the ZAMS shifted to a series of distances. We estimated the uncertainty on the best fit distances as the distances at which we found that $\chi^2 = \chi^2_{best}+1$.

2.6.1. Choice of ZAMS

We examined two empirical ZAMS (Turner 1976, 1979; Schmidt–Kaler 1982) in order to select the best representation of the σ Ori cluster's main sequence. Both ZAMS closely follow the cluster's main sequence.

We use both versions of the ZAMS because although Turner's ZAMS follows the locus of cluster members on the CMD nearly perfectly, it does not include U band photometry. The ZAMS from Schmidt–Kaler does not trace the locus of our data quite as well, but includes U band photometry. The U band ZAMS values are valuable because the slope of the ZAMS is ∼6 on the $(\mathrm{U}-\mathrm{B})_0$ vs. V_0 CMD and ∼4.5 on the $(\mathrm{U}-\mathrm{V})_0$ vs. V_0 CMD. These slopes are much shallower than the slope of ∼18 on the $(\mathrm{B}-\mathrm{V})_0$ vs. V_0 CMD. This makes the best fit distance less sensitive to small errors in the reddening correction.

2.6.2. The Empirical ZAMS of Turner

We shifted the ZAMS of Turner (1976, 1979) to match the Pleiades cluster which has in turn been matched to the Hyades cluster (An et al. 2007). The Hyades cluster has [Fe/H]=+0.14±0.05 and a distance modulus of 3.33±0.01 (Perryman et al. 1998). The Pleiades has a nearly solar [Fe/H] of ∼+0.04±0.03 (An et al. 2007).

The left panel of Figure 4 shows the 10 members of the cluster which have reached the ZAMS. The lines show the ZAMS of Turner shifted to distances ranging from 350 pc to 464 pc.

We estimated the most probable distance to the cluster by calculating χ^2_ν for the ZAMS shifted to 1000 candidate distances between 280 pc and 530 pc. For each candidate distance we calculated χ^2_ν from the separation between the empirical ZAMS and the $(\mathrm{B}-\mathrm{V})_0$ colors of the nine main sequence cluster members for which we have directly measured B−V

colors, or spectral types. We used the $(B-V)_0$ colors as the dependent variable for the χ^2_ν calculation because the uncertainties in the colors dominate the uncertainties on the estimated distance. Our best fit distance is 442±20 pc.

The small value, 0.5, of our best χ^2_ν suggests that we have over–estimated the uncertainties on the $(B-V)_0$ colors.

2.6.3. The Empirical ZAMS of Schmidt–Kaler

Using the ZAMS of Schmidt–Kaler (1982), also shifted to match the Pleiades, on the $(B-V)_0$ vs. V_0 CMD, we find a best fit distance of 462^{+14}_{-35} pc. This is 1 σ larger than the best fit distance using the Turner (1976) ZAMS.

The right panel of Figure 4 compares the data for the main sequence cluster members to the ZAMS on the $(U-B)_0$ vs. V_0 CMD. The best fit distance is 488^{+18}_{-20} pc. The right panel of Figure 4 plots $(U-B)_0$ colors corrected using the expected value of E(U−B)=0.04. The V data have been corrected for reddening using the A_V derived from the mean E(B−V) in Section 2.2. If the (U−B) colors were corrected by the mean value of E(U−B)=0.02, then the derived distance would be 458^{+15}_{-17} pc.

We also estimated the cluster's distance on the $(U-V)_0$ vs. V_0 CMD. The best fit distance is 492^{+18}_{-31} pc using a normal reddening law and the observed E(B−V) of $0.^m06\pm0.005$, or 457^{+28}_{-16} pc using the measured value of E(U−V)=$0.^m08\pm0.03$. The distances estimated using the U band photometry combined with a standard reddening law are 2σ larger than the distances estimated from colors corrected by the mean measured E(U−B) or E(U−V). They are also 2σ larger than the distance estimated from the (B−V) colors. This may indicate that the cluster has a non–standard reddening law with E(U−B)=0.36E(B−V).

An alternative is to use the reddening corrected $(U-B)_0$ and $(U-V)_0$ colors that correspond to the observed spectral types. Doing that, we find distances of 452±14 pc and 447^{+13}_{-7} pc respectively. Since there is much more scatter in the observed U−B colors (which we used to get the U−V colors) than in the observed B−V colors, using the spectroscopic colors to estimate the cluster's distance may be more accurate.

Table 2 collects all of the distances we estimated using different color indices, reddenings, ZAMS, and metallicities.

2.6.4. *The Best Distance Estimate*

It is not straight–forward to combine the best–fit distance estimates into a single best–fit distance. The various results we obtained using the Schmidt–Kaler (1982)) and the Turner (1976) ZAMS should not simply be averaged because the differences between them are systematic, not random. Given the difficulties correcting for the reddening on the V, U−B and V, U−V CMDs, we give more weight to the distance estimates we found using the spectroscopic colors. These distance estimates, combined with the distance estimates from the V, B−V CMD, indicate a best–fit distance of 444±20 pc assuming solar metallicity. Correcting for the lower metallicity of the cluster brings the distance estimate down to somewhere between 400 pc and 440 pc. At the most likely metallicity, the best–fit cluster distance is 420±20 (random)±25 (systematic) pc or 420±30 pc. As knowledge of the cluster's metallicity is refined, the best estimate of the distance modulus will shift and the systematic component of the uncertainty will be reduced. It is important to note that for the purposes of comparing the cluster to solar metallicity isochrones, the isochrone should be shifted to be $\sim 0^m.12$ fainter to compensate for the lower luminosity of a sub–solar metallicity isochrone. For low–mass stars line–blanketing will shift the isochrone by an additional amount that will depend upon the color index used on the CMD.

The final line of Table 2 lists the best "average" distance estimates for five assumed values for the cluster's metallicity. The assumed metallicities range from +0.04 to −0.27. The uncertainties include only the random component of the uncertainty.

3. Discussion

An improved distance estimate for the σ Ori cluster will impact the conclusions of previous research by varying degrees, depending upon what distance the authors assumed.

3.1. Implications for the Age of the Cluster

The position of σ Ori C on figure 3 suggests a cluster age of ∼2.5 Myrs. This is consistent with the age of 2–3 Myrs estimated from the low–mass stars by Sherry et al. (2004). Sherry et al. (2004) did not correct for the small reddening, or the sub–solar metallicity of the cluster. An A_V of 0.19 would make the low–mass stars a bit brighter and therefore slightly younger. A sub–solar metallicity should make the low–mass stars bluer at a given spectral type. This would make the cluster's locus on the CMD fainter (thus a bit older). The net effect on the estimated age is likely to be small, but without isochrones matched to the cluster's metallicity, the net effect is difficult to estimate.

3.2. Adjustments to the Cluster's X–Ray Luminosity Distribution Function

Franciosini, Pallavicini, & Sanz-Forcada (2006) compared the X–Ray Luminosity Distribution Function (XLDF) of candidate low–mass members of the σ Ori cluster to the XLDFs of ρ Oph, the Orion nebula cluster (ONC), and the Cha I star forming regions. They found that the median 0.1–4 keV luminosity of K–type candidate members of the

σ Ori cluster is a factor of 3 to 5 fainter than that for the ONC or Cha I, but comparable to that of ρ Oph. They also found that the median X–ray luminosity for σ Ori cluster M–type candidate members is significantly lower than those of all three star forming regions. Franciosini, Pallavicini, & Sanz-Forcada (2006) note that the discrepancy between the observed σ Ori XLDF and the ONC or Cha I XLDFs may be due in part to contamination of the membership list by field stars. They report that their sample includes 45 candidate σ Ori cluster member that were selected from just photometric data and that were not detected with XMM. The discrepancy between the XLDFs of the ONC and Cha I and the XLDF of the σ Ori cluster is significantly reduced if most or all of these 45 candidate cluster members are assumed to be non-members.

Franciosini, Pallavicini, & Sanz-Forcada (2006) assumed the Hipparcos distance of 352 pc for σ Ori. Also, they used an XLDF for the ONC that assumed a distance of 470 pc (Flaccomio et al. 2003). Recent work shows that the ONC is at a distance of 414$\pm$7 pc (Menten et al. 2007). Using our best fit distance of 420 pc and the new ONC distance, the ratio of the median X–ray luminosities would be larger by nearly a factor of 2. This, combined with the high probability that many of the 45 photometric candidate members that were not detected with XMM are non–members, may account for the apparent faintness of σ Ori cluster members relative to the ONC.

3.3. σ Ori B

Since σ Ori B is observed to orbit σ Ori A (Heintz 1974, 1997; Frost & Adams 1904), it is at the same distance as σ Ori Aa and Ab. Yet, σ Ori B is consistently $\sim 0.^{m}6$ brighter than the ZAMS which fits all of the other high–mass cluster members. This suggests that σ Ori B is a close binary just as σ Ori A is. Alternatively, our assumed colors could be slightly wrong. If σ Ori B is a bit hotter and bluer than expected for a B0.5V star, it would

be more consistent with the best fit ZAMS. A sufficiently blue value of $(B-V)_0$ would be within 1σ of the standard color of a B0.5V. However, sufficiently blue $(U-B)_0$ or $(U-V)_0$ colors would be difficult to reconcile with the observed B0.5V spectral type. We feel that a close binary companion is the more likely explaination.

4. Conclusions

From Figure 4 it is clear that the σ Ori cluster must be more distant than the nominal 350 pc Hipparcos distance for σ Ori. We estimate a distance of 420±30 pc for the cluster, assuming an [Fe/H] of −0.16, or 444 pc assuming solar metallicity. This is consistent with, but significantly more precise (7%) than the Hipparcos distance (30%). Our distance estimate is consistent with the estimated distance to Orion OB1b. Most of the older age estimates for the cluster assumed a distance of 350 pc. Our more tightly constrained distance shows that the cluster age must be closer to the young end of the range of the estimated ages. This places the age of the cluster in the range of 2–3 Myrs.

Sixteen of the 19 stars in our sample are probable members of the σ Ori cluster. HD 37564 is too bright to be a cluster member. HD 294279 is too faint to be a cluster member. If HD 37333 is in fact an equal mass binary, it is likely to be a cluster member.

The existence of a tight main sequence among the O, B, and A stars of the σ Ori cluster suggests that any other clusters within the Orion OB1a and Orion OB1b groups (such as the 25 Ori cluster (Briceño et al. 2005)) should also have tight main sequences.

This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France. Stony Brook University's participation in the SMARTS consortium is made possible by generous contributions by the Vice President for Research, the Provost, and the Dean of Arts and Sciences.

WHS was supported in part by the NAI under Cooperative Agreement No. CAN-02-OSS-02 issued through the Office of Space Science. The NSO and the NOAO are operated by AURA for the National Science Foundation.

SJW was supported by NASA contract NAS8-03060.

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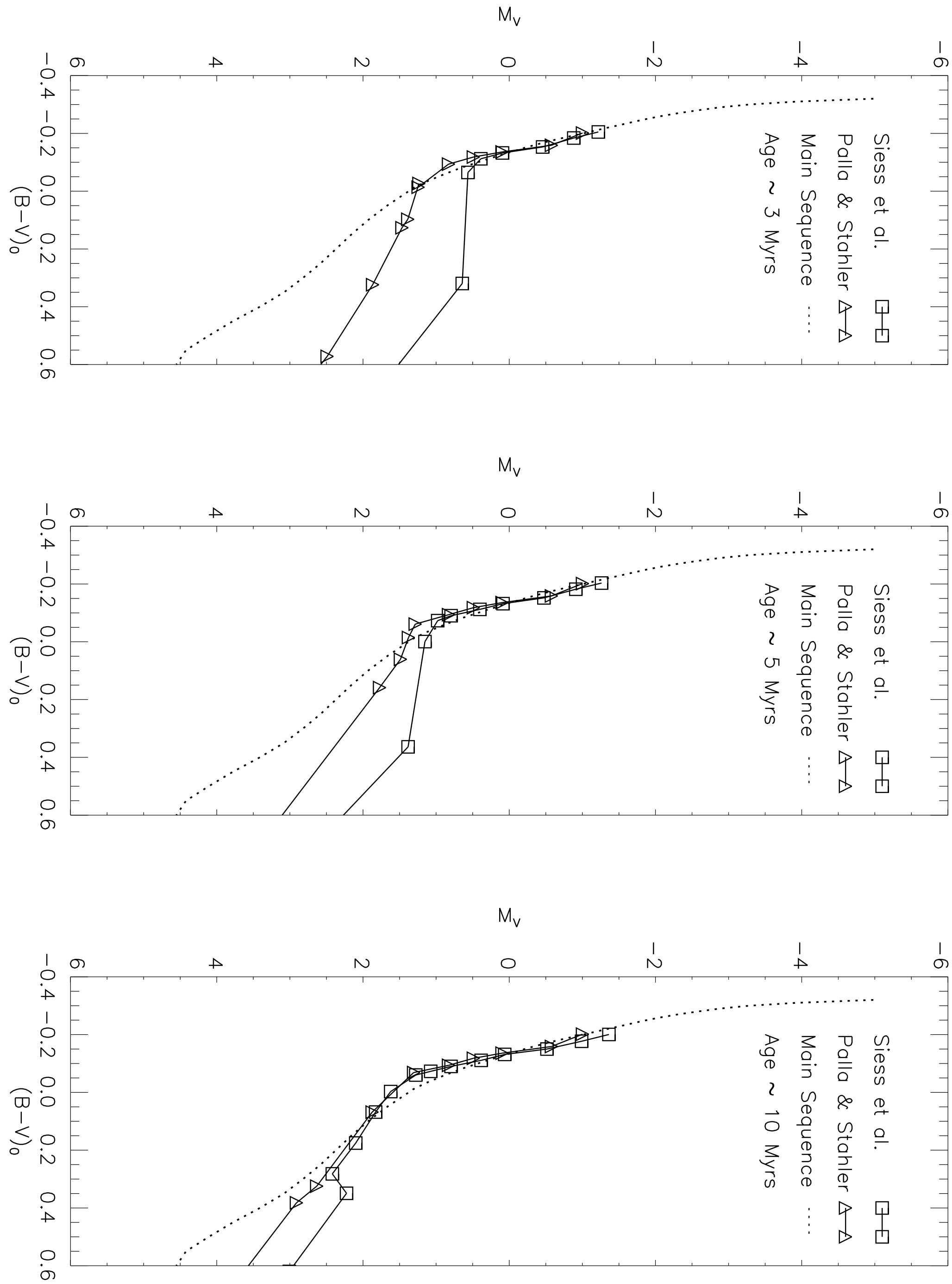

Fig. 1.— The three panels of this figure illustrate the evolution of the main sequence turn–on from an age of ∼3 Myrs (Left) through an age of ∼5 Myrs (Middle) to an age of ∼10 Myrs. At ages of ∼3 Myrs and ∼5 Myrs both the Siess, et al. (2000) and the Palla & Stahler (1999) isochrones join the ZAMS (Turner 1976, 1979) near (B−V)$_0$ of 0.0. The late A–stars are on the ZAMS only for the ∼10 Myr isochrones.

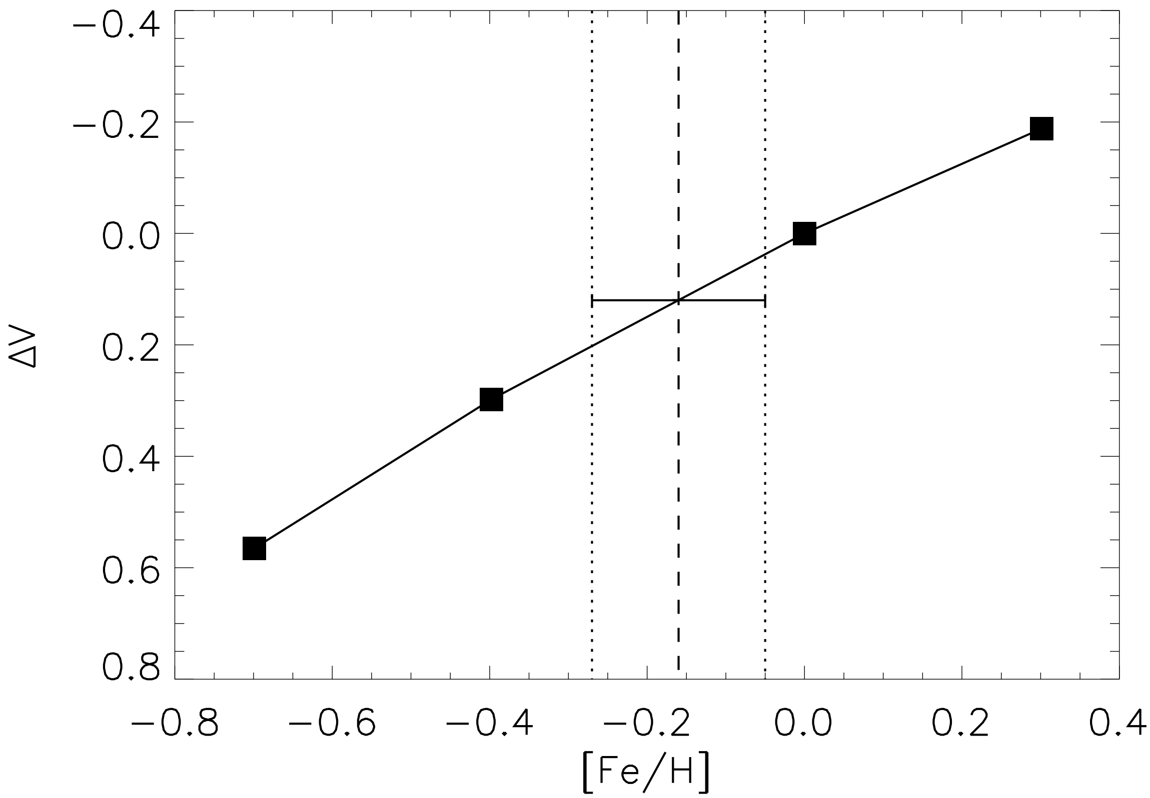

Fig. 2.— The change in the M_V of the 2 Myr isochrones of Lejeune & Schaerer (2001) at a fixed (B−V) color of $-0.^m21$ as the metallicity ([Fe/H]) increases from [Fe/H]=−0.7 (z=0.004) to [Fe/H]=+0.30 (z=0.040). The dashed line marks the average value of [Fe/H] for Orion (Cunha, Smith, & Lambert 1998). The two dotted lines are the ±1 σ values for [Fe/H]. The horizontal bar marks the predicted ΔV between a solar metallicity isochrone and an isochrone with [Fe/H]=-0.16. From this plot we conclude that Orion's sub–solar metallicity will make the ZAMS fainter by between $0.^m04$ and $0.^m2$.

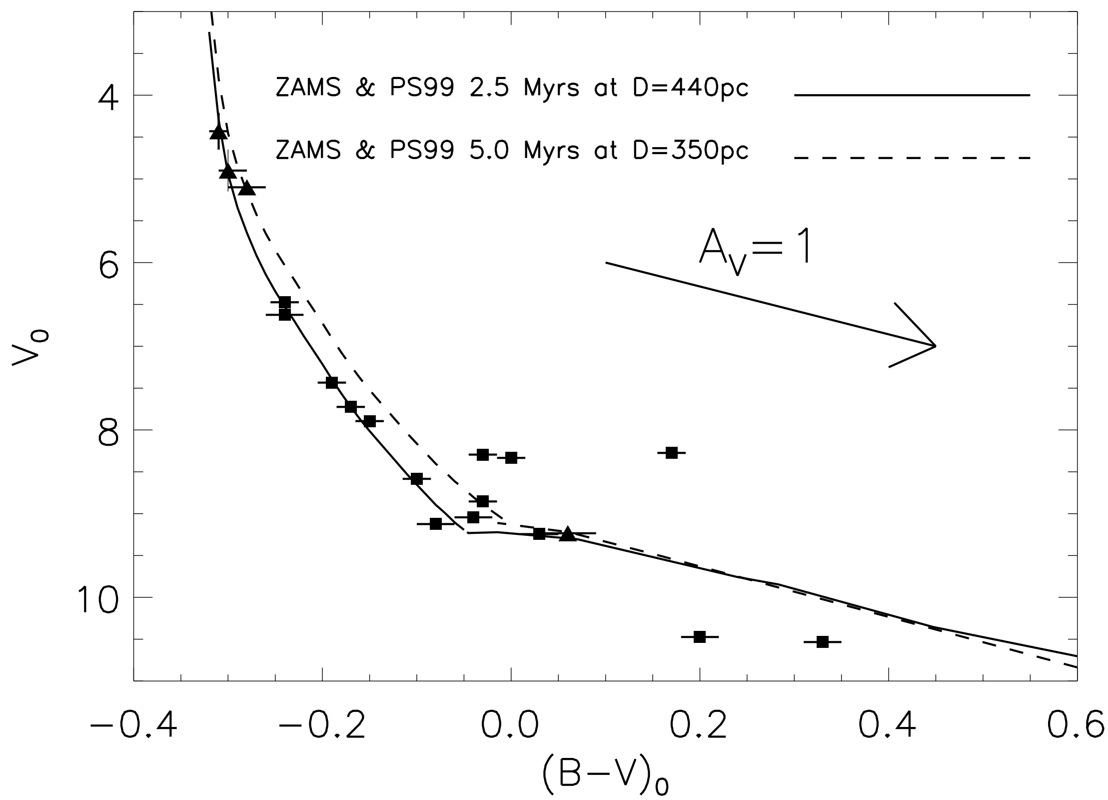

Fig. 3.— This color–magnitude diagram compares the dereddened (B−V) colors and V magnitudes of the early type stars within 30′ of σ Ori AB to the expected locus of cluster members for distances of 440 pc and 350 pc. The solid line is an empirical solar–metallicity ZAMS (Turner 1976) plus a 2.5 Myr isochrone (Palla & Stahler 1999) at a distance of 440 pc. The 2.5 Myr isochrone matches the cluster age estimated from the low–mass members (Sherry et al. 2004) as well as the position of σ Ori C. The dashed line is the ZAMS at a distance of 350 pc and a 5 Myr isochrone that was chosen to match the position of σ Ori C. The triangles mark the positions of σ Ori Aa, σ Ori Ab, σ Ori B, and σ Ori C. These four stars were placed on the CMD using values of $(B-V)_0$ predicted from their spectral types because no reliable measured values of (B−V) were available. The squares mark the positions of the remaining stars from Table 1.

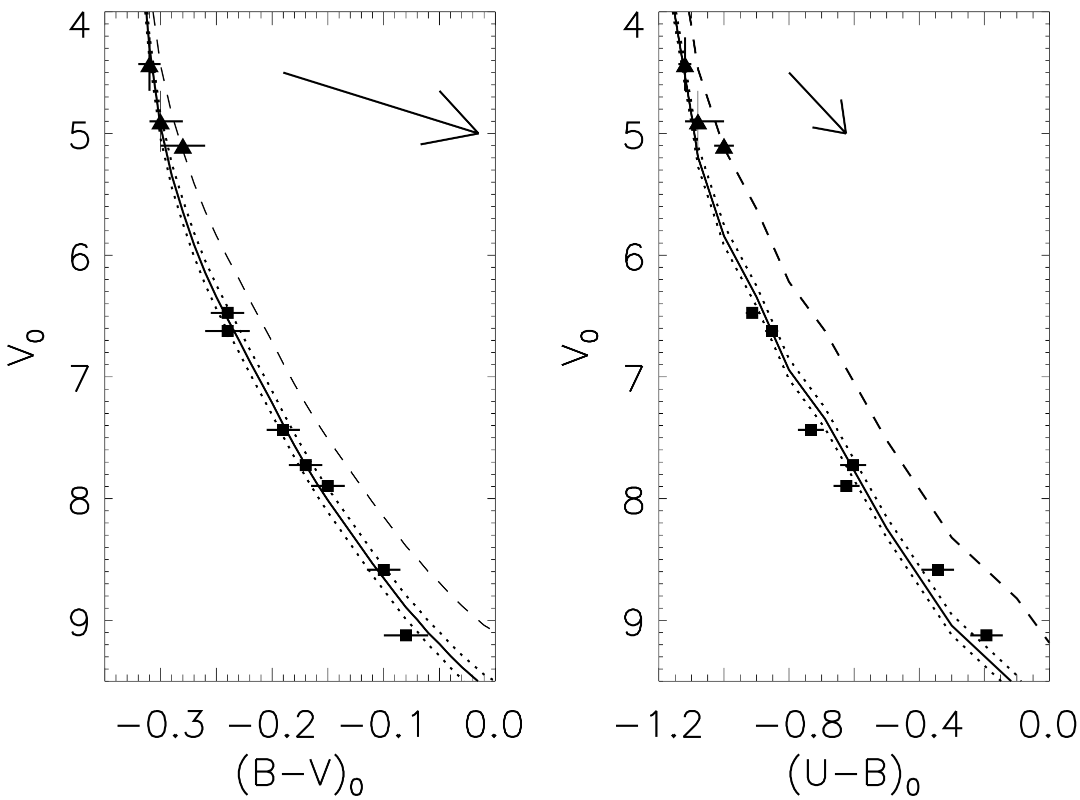

Fig. 4.— **Left**: This color–magnitude diagram compares the corrected and derived values of $(B-V)_0$ and V magnitude for likely cluster members (see Table 1) along with the solar–metallicity zero age main sequence of Turner (1976) shifted to the best fit distance (solid line), the best fit $\pm 1\sigma$ distances (dotted lines), and the Hipparcos distance (dashed line). The triangles mark the colors and magnitudes derived for σ Ori Aa, σ Ori Ab, and σ Ori B. The color of σ Ori Ab was derived by assuming that it lies on the ZAMS at the same distance as σ Ori Aa, so σ Ori Ab was not used to derive the best fit distance. The filled squares show the dereddened colors and magnitudes for the remaining main sequence B–stars identified as cluster members in Table 1. The arrow shows a reddening vector for $A_V=0.^m5$. **Right**: This color–magnitude diagram compares the corrected and derived values of $(U-B)_0$ and V magnitude for likely cluster members (see Table 1) along with the zero age main sequence of Schmidt–Kaler (1982) shifted to the best fit distance (solid line), the best fit $\pm 1\sigma$ distances (dotted lines), and the Hipparcos distance (dashed line). The plot symbols are the same as on the right panel. The arrow shows a reddening vector for $A_V=0.^m5$.

Table 1. Adopted Values

ID	U−B	$(U-B)_0$ [b]	B−V	$(B-V)_0$ [b]	Err	V [1]	Sp. Type [2]	D(′)	A_V	Member	Notes
σ Ori Aa	–	−1.12[h]	–	−0.31	0.01	4.4[3]	O9V[a]	0.00	0.19	MS*	Calculated
σ Ori Ab	–	−1.08[h]	–	−0.30	0.01	4.9[3]	[B0V?][8]	0.00	0.19	MS	Calculated
σ Ori B	–	−1.00	–	−0.28	0.02	5.16[3]	B0.5V[a]	0.00	0.19	MS*	Calculated
σ Ori C	–	+0.06	–	+0.06	0.03	9.42	A2V	0.20	–	PMS	V from Sherry et al. (2008)
σ Ori D	−0.81	−0.84	−0.18	−0.24	0.02	6.81	B2V	0.22	0.19	MS*	
σ Ori E	−0.87	−0.84	−0.18	−0.24	0.014	6.66	B2Vp	0.69	0.19	MS*	Peculiar, Variable
HD 294272	−0.05	−0.10	+0.03	−0.04	0.015	8.48	B9.5III[9]	3.12	0.22	PMS?	ADS4240B
BD −02 1323C	−0.30	−0.37	−0.04	−0.11	0.02	8.77	B8V[g]	3.25	0.22	MS*	
HD 294271	−0.56	−0.58	−0.11	−0.17	0.01	7.91	B5V[c]	3.47	0.19	MS*	ADS4240A; ADS4240B is 68″ away.
HD 37525	−0.58	−0.58	−0.09	−0.17	0.01	8.08	B5V[5]	5.11	0.25	MS*	May be B5III[5] ; has a faint 0.″45 companion[4]
HD 294273	+0.07	+0.07	+0.26	+0.2	0.03	10.66	A7–9[6]	8.68	0.19	No	HDE Spectral Type: A3
HD 37564	+0.15	+0.10	+0.23	+0.17	0.03	8.46	A5/7	8.74	0.19	No	>1 mag. brighter than isochrone.
HD 37633	−0.36[7]	−0.20	+0.03	−0.06	0.04	9.04	B9	16.00	0.28	PMS	Variable (V1147 Ori)
HD 37333	−0.06	−0.07	+0.06	+0.00	0.02	8.52	A0V	18.60	0.19	PMS?	Binary or Non–Member
HD 294279	+0.03	+0.01	+0.39	+0.37	0.03	10.72	F3[6]	19.34	0.06	OB1a?	See Section 2.5.4
HD 294275	+0.01	+0.07	+0.09	+0.03	0.03	9.43	A1V[g]	20.45	0.19	PMS	
HD 37545	−0.15	−0.20	−0.02	−0.06	0.02	9.31	B9V	21.46	0.12	MS*	
HD 37686	−0.09	−0.10	+0.02	−0.04	0.015	9.23	B9.5V	22.64	0.19	(P?)MS	
HD 37699	−0.69	−0.58	−0.13	−0.17	0.01	7.62	B5V	25.79	0.12	MS?*	Radial velocity may be inconsistent with membership[4]

[1]These values are not corrected for extinction, except for σ Ori Aa, Ab, and B.

[2]Spectral types are from Houk & Swift (1999) except where otherwise noted.

[3]These are reddening corrected magnitudes.

[4](Caballero 2007)

[5]Houk & Swift (1999) list a spectral type of B5III, but point out that the differences between class V and class III are subtle in B stars. We have adopted the spectral classification from Schild & Chafee (1971).

[6]Spectral types from our SMARTS 1.5m observations. See Section 2

[7]This star seems to have a U band excess.

[8]Spectral type estimated from ΔV between σ Ori Aa and Ab.

[9]This spectral type is from Guetter (1981). We have included this star because we doubt the luminosity class (see note 5). If the luminosity class is correct, this star is unlikely to be a member of the cluster.

[a]Spectral types from Edwards (1976)

[b]Reddening free colors are from Kenyon & Hartmann (1995) except where otherwise noted.

[c]Spectral types from Schild & Chafee (1971)

[g]Data from Guetter (1981).

[h]Data from Table 12 of Schmidt–Kaler (1982).

Table 2. Distance Estimates (pc)

ZAMS/Color	$\frac{Fe}{H}$=+0.04	$\frac{Fe}{H}$=0.0	$\frac{Fe}{H}$=−0.05	$\frac{Fe}{H}$=−0.16	$\frac{Fe}{H}$=−0.27	Color Correction
Turner B−V	442±20	436±20	428±19	412±19	397±18	Mean E(B−V)
Schmidt-Kaler B−V	462^{+14}_{-35}	456^{+14}_{-35}	448^{+14}_{-34}	431^{+13}_{-33}	415^{+13}_{-31}	Mean E(B−V)
Schmidt-Kaler U−B	488^{+18}_{-20}	481^{+18}_{-20}	473^{+17}_{-19}	455^{+17}_{-19}	438^{+16}_{-18}	Mean E(B−V)[1]
Schmidt-Kaler U−B	458^{+15}_{-17}	452^{+15}_{-17}	444^{+15}_{-16}	427^{+14}_{-16}	411^{+13}_{-15}	Mean E(U−B)
Schmidt-Kaler U−B	452±14	445±14	438±14	422±13	406±13	SpT[2]
Schmidt-Kaler U−V	492^{+18}_{-31}	485^{+18}_{-31}	477^{+17}_{-30}	459^{+17}_{-29}	442^{+16}_{-28}	Mean E(B−V)[1]
Schmidt-Kaler U−V	457^{+28}_{-16}	451^{+28}_{-16}	443^{+27}_{-16}	426^{+26}_{-15}	411^{+25}_{-14}	Mean E(U−V)
Schmidt-Kaler U−V	447^{+13}_{-7}	441^{+13}_{-7}	433^{+13}_{-7}	417^{+12}_{-7}	402^{+12}_{-6}	SpT[2]
Combined Estimate[3]	450±20	444±20	436±20	420±20	404±20	

[1]Assuming a standard reddening law with E(U−B)=0.72E(B−V).

[2]We adopted the colors for each star's spectral type given by Kenyon & Hartmann (1995).

[3]The estimated uncertainties include only the random error from the fit. The systematic uncertainty from the choice of ZAMS is at least 10 pc. Combined with the uncertainty on the metallicity, the total systematic error is ∼25 pc.